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Could Europe have more mini hydro sites? A suitability analysis based on continentally harmonized geographical and hydrological data ☆

K. Bódis *, F. Monforti, S. Szabó

European Commission, Joint Research Centre, Institute of Energy and Transport, Renewable Energy Unit, Via E. Fermi 2749, TP450, I-21027 Ispra (VA), Italy

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ABSTRACT

The paper introduces a transparent methodology to assess new suitable locations for mini and small hydro power plants in Europe. The expansion of hydro electricity production is a policy focus not only in Europe, but in the US (Hydropower Regulatory Efficiency Act of 2013) and in the developing world as well. The analysis of the technical potential points out the exact geographical locations and their corresponding capacities instead of only a theoretical potential; therefore it can serve as a reference for the policy debate over the sustainable management of water resources. This debate is reflected already in two major European policies: the Water Framework Directive (WFD) (2000/60/EC) and the RES Directive (2009/28/EC) on the promotion of the use of energy from renewable sources. As both policies have major influence on the priorities of water use, it is important to identify water management practices capable of accommodating sustainable energy purposes while maintaining water quality objectives at the same time. As the WFD poses limitation on the further expansion of large scale hydro options in the European water bodies, the present study focuses on local mini and small hydropower options and their suitability mapping. The presented, geographically explicit method is based on geospatial analysis and the results can contribute to the prioritization of potential hydro power sites in order to improve water quality and its use for energy simultaneously.

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* Corresponding author. Tel.: +39 33278 6582; fax: +39 033278 9992.
E-mail address: katalin.bodis@geography.hu (K. Bódis).

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1. Introduction

Large scale integration of electricity from renewable energy sources (RES) into the power grid has become a major issue in meeting the ambitious European renewable energy targets set in the European Commission (EC) legislations [1] and confirmed in the action plans of the Member States (EU27) [2–4].

According to these plans, solar electricity installed capacity is expected to increase from 26 GW in 2010 to 90 GW foreseen for 2020, while in the same period wind electricity installed capacity is expected to rise from 85 GW to 211 GW in EU27. The variability of wind and solar resources creates new challenges in energy regulation: curtailment and the setting up of additional storage capacity are traditional answers to the need of making the increasing RES share available, even if with many shortcomings and economic losses [5,6].

Novel techniques introduced by spatial analysis and suitability mapping can also help to overcome power deficiencies caused by intrinsic resources intermittence and to attain more advanced load management and balancing. An important element of these techniques to increase reliability is to better estimate the availability of the various renewable energy sources. Other element is to find flexible production to facilitate load regulation while demand side management techniques also can help to solve integration problems [7,8].

Hydropower has always been playing key roles in all these aspects: some of the hydro electricity production can be made quite responsive to load management requirements, while pumping storages can consume electricity in low demand-low price periods, and provide it back profitable during periods of peak demand. Hydro output is, in general, more predictable than using solar and wind resources, since large hydro plants are operating largely under full human control, except in the case of long dry periods.

With the increase of the other RES in the electricity generation portfolio and with the rapid developments in hydrological data procession hydropower can become a more central element of integration. Its role is expected to become more crucial even in Europe where high part of the existing hydro potential is already utilized [9,10].

Three main development pathways can be identified for the existing and close future hydropower infrastructure pool: at first, better management of the output of the big reservoirs can provide more substantial contribution in peak hours complementing the traditional base-load energy sources such as natural gas, coal, biomass and so on. Secondly, the identification of new locations for pumping stations [11] and their increased application can contribute to improve load management by putting more back-up storage capacity in the system. Thirdly, additional mini- and small-hydropower plants could provide an important clean, renewable and cost-sustainable complement to the variable output of the other local solar and wind resources, especially in case of RE distributed generation model.

This latter option could achieve these positive impacts on RES integration without the often criticized adverse environmental effects of big hydro projects and the somewhat problematic site selection issues of the pumping storages [11]. Synthesis and taxonomy of characteristics, advantages and disadvantages of hydropower installations in different sizes and technologies can be discussed from several aspects. A literature-based comparison is given in Annex I.

The present paper focuses on this third option and assesses the possible pathways of further development of the mini- and small-hydropower production systems based on run-of-river hydropower schemes (stations using the natural water flow for electricity production, without being complemented by some water storage infrastructure). This paper also complements the existing literature [9,10,12] on theoretically available hydro energy potential analysis proposing an analysis based on a methodology that derives a technical hydro potential directly from hydrological, elevation and technological datasets and GIS layers enabling to select potential hydropower sites with capacities.

On summary, Section 2 introduces the state of hydropower in Europe and the main data sets on which the present study is based. The original GIS-based model developed for identifying potential sites of new small hydropower plants is described in Section 3. The proposed approach (Fig. 1) is based on digital elevation data and derived river networks [13–15] complemented by hydrological data obtained from a model originally developed for flood forecasting and flood risk assessment [16], including climate change scenarios [17].

It is worth anticipating that the adaption of the available outputs of the hydrological model [16,17] to mini- and small-hydro potential assessment has required solving many data discrepancies and dealing with spatial challenges originated in different scales, resolution and combining different elements of hydrography and geomorphology with techno-economic criteria. In general, the datasets used in this study have the relevant advantage of being harmonized on a continental scale as they were collected, generated, validated and used primarily for flood risk and water management in the EU.

The main results of the study both in terms of capacity and suitable location of power stations are presented in Sections 4 and 5 focusing on results validation through comparison with available data sets for both aggregate and geographically explicit indicators. Finally, in Section 6 conclusions put the concrete replicable results presented here in the frame of new discussions over the attainable resource hydro potentials in Europe.

2. Hydropower potential in EU – overview and data sources

Hydropower potential can be defined using different approaches [18]. The *'gross'* hydropower potential is defined as "the annual energy potentially available, when all natural runoff in a country is harnessed down to the sea level (or to the border line of the country) without any energy losses". The *'technical'* hydropower potential gives the potential electric power "that could be, or have been developed, considering current technology, regardless of economic and other restrictions". The *'economic'* hydropower potential is "that portion of the technical potential, which can, or has been developed, at costs competitive with other energy resources". Finally, for estimating the

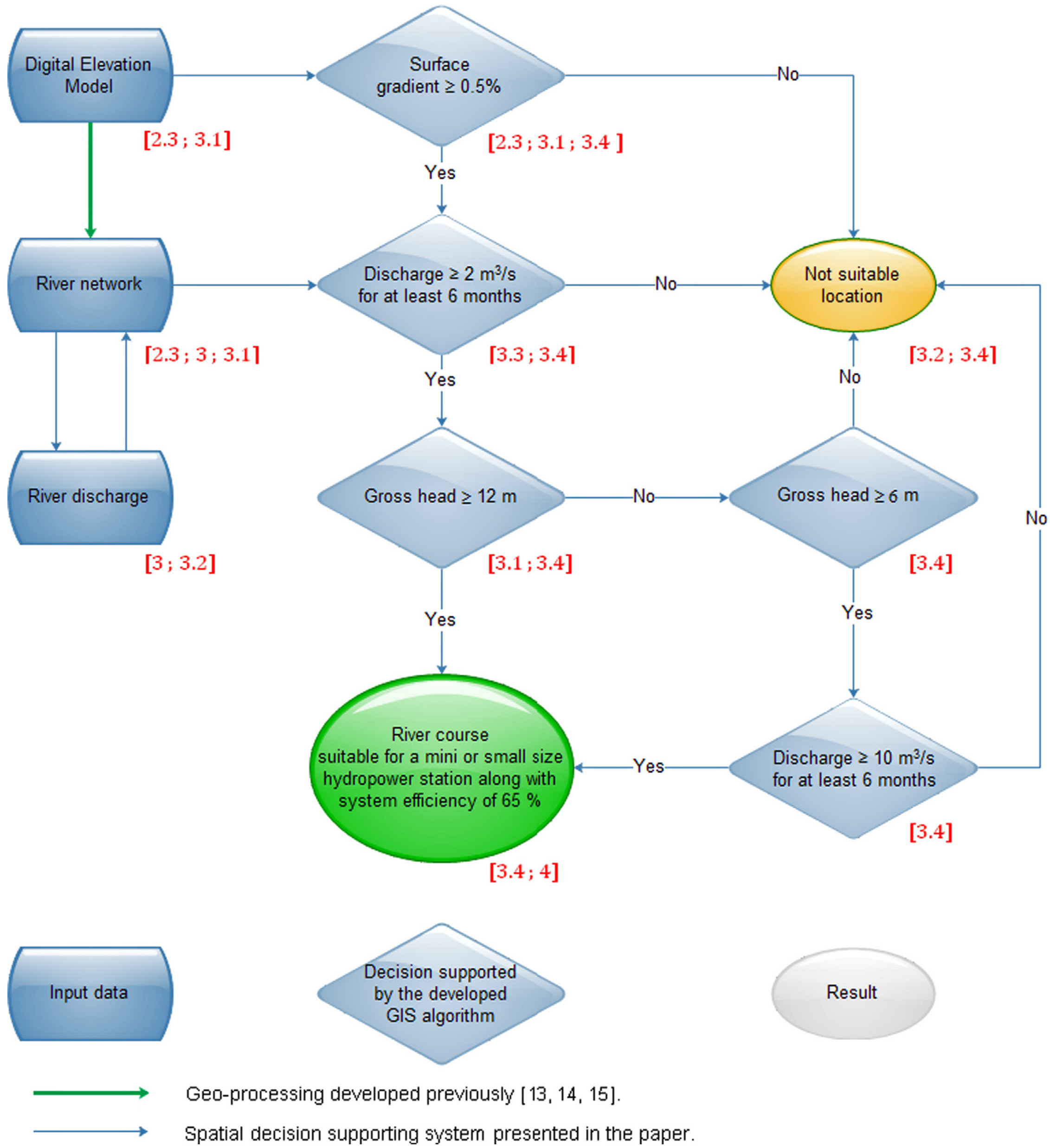

Fig. 1. The flowchart of the selection of potential locations of mini and small hydroelectric stations according to the technological requirements of turbine systems against hydrographical parameters.

'exploitable' hydropower potential, additional environmental, socio-economical or other restrictions are also considered [18].

2.1. Status and perspective of hydropower potential and utilization in Europe

In the last decade substantial developments have taken place in two dominant policy drivers that will have major impacts on the future of hydropower in Europe: the Water Framework Directive (WFD) (2000/60/EC) [19] and the RES Directive (RED) (2009/28/EC) [1]. The WFD brings about more stringent water quality measures while the RED sets higher targets for RE generation. There is a potential clash of interest between these two policy domains as the WFD established new procedures, quality objectives which potentially create new barriers for mini-hydro while the integrated multi-source approach taken by RED is meant to end up in higher hydropower shares in the electricity generation portfolio. This latter effect is caused not only by the setting of absolute legally binding targets for RES penetration, but by the fact that the proper integration of the other (so called "intermittent") RE sources like e.g., wind and solar require to be backed by more constant and flexible sources of renewable energy. The hydro option could be a perfect match in this respect. More in detail, the Water Framework Directive requires for each River Basin District to set up a River Basin Management Plan [19] setting environmental objectives for all the water bodies within the River Basin District based upon a detailed analysis of the pressures they are subject to Amongst the various water uses, hydro energy obviously could pose both flow regulation risk, and physical or morphological alteration risk. Moreover, the more stringent water quality requirement of WFD can result in longer permission procedures, identification of larger areas excluded from energy purposes.

Nevertheless, it seems this stricter regulatory framework has not stopped the development of mini-hydro in Europe as in

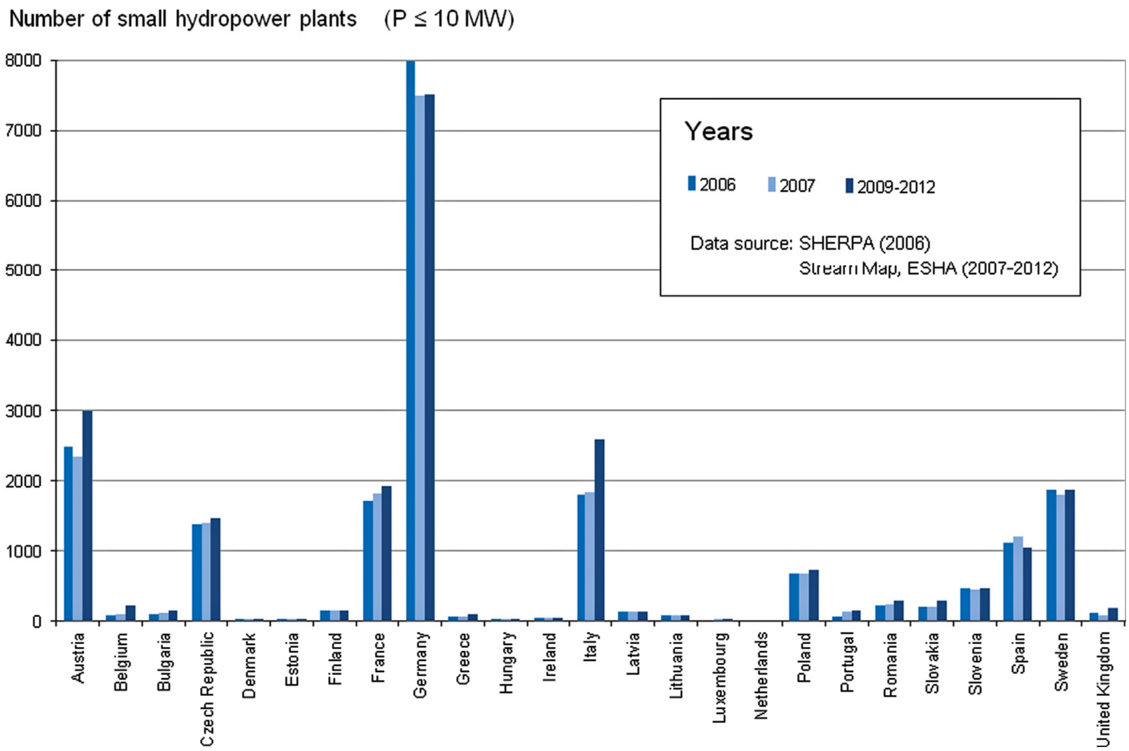

Fig. 2. Development of number of small hydropower stations of 25 member states of the European Union. (No data is available for Croatia, Cyprus and Malta.) The total number of installations in the 25 cited Member States amounted to 20,953 in 2006, 20,597 in 2007 and 22,686 in the period 2009–2012.

general the number of small hydropower plants is increasing in the member states of the European Union (Fig. 2) [20–22].

The reason for this overall success on mini-hydro installations can be looked for in the pressure towards RE production and integration. The RES Directive (as it follows a very distinct objective from the WFD) gives clearly positive incentives to the hydro energy developments. The integration of larger shares of electricity produced from renewable energy sources to the existing grid requires increased availability of more flexible power producers. Hydro electricity could serve as such an option; however optimizing this portfolio share requires the multi criteria optimization, partially still to be achieved in Europe.

In order to harmonize the somewhat contrasting policy drivers a meaningful policy debate has to be carried out amongst all related stakeholders, in the spirit of the WFD itself, for which water management decisions take account of all potential uses, risks and values (irrigation, agriculture, flood control, recreation, nature, habitat and energy). Controllable information on potential site locations is essential for supporting decision making on extending one of these uses (i.e. energy).

In order to avoid the NIMBY syndrome ("not in my backyard" attitude expressing low public acceptance or opposition by local residents to a proposal for a new installation because it is going to be too close to them) in this respect, the arguments over the potential sites should not take place on a case by case basis, but on an integrated large scale planning bases [23,24], also foreseen by the WFD River Basin Management planning procedures. This requires that the hydro energy potential is not only given by national theoretical figures, but the sets of potential sites have to be identified in order to select the most suitable and sustainable places from energetic and environmental protection point of view. The policy debate having an important effect can be stimulated by the identification of the potential site options and this is one of the reasons for which the actual estimate of hydro potential has been deeply debated in the current scientific literature.

2.2. Current estimates of European potential hydropower

Amongst the related literature general distribution of hydropower capabilities across Europe has been outlined and extensive methodological work can be found for the identification of the theoretically available hydropower potential e.g., [9,25–28], and a wide range of statistical data is available indicating the hydropower potential on different levels (i.e. gross theoretical, technically exploitable, economically feasible), e.g., [21,22,29].

However, the theoretical hydropower potential gives an absolute ceiling and it is estimated by physical parameters based on geographical and hydrographical data. Moreover, different sources and methodologies can also result in different figures (Table 1).

Publically available data sets show derived technical potentials [21,22,29] based on the above mentioned theoretical potential figures as an important step towards trying to create a strong foundation for an economic potential analysis. Economic potential is a crucial element for the policy discussion over the role of hydro electricity in the future European energy generation portfolio. Nevertheless, the literature on methodological guidelines and descriptions of estimating these essential technical and economic exploitable potentials are quite limited. One of the objectives of this study is to develop and exhaustively present a methodology based on harmonized European hydro- and geo-data sets, making the estimates found here unbiased and comparable.

2.3. Primary data sources for hydropower potential estimate in EU-27

The present study is based on several primary data sources that were harmonized, exploited and combined following the procedure described in Section 3. Here these primary data sets are briefly listed and described.

Information related to the **topography** (e.g., estimated surface gradient, head) had been derived from the high-resolution

Table 1
Gross theoretical, economically exploitable and economically feasible hydropower potential [GWh/year]. Comparison of publically available different data sources.

	World Energy Council [22]			Hydropower & Dams, World Atlas 2009 [23]			ESHA[a] [24]		
	GTC[b]	TEP[b]	EFP[b]	GTC	TEP	EFP	GTC	TEP	EFP
Austria	75,000	56,000	56,000	90,000	56,000	~53,200	100,000	73,000	56,000
Belgium	n/a	n/a	n/a	~600	n/a	400	n/a	n/a	483
Bulgaria	27,000	15,000	12,000	19,810	14,800	n/a	19,811	n/a	4520
Croatia	10,000	8000	n/a	20,000	12,000	10,500	n/a	n/a	n/a
Cyprus	n/a	n/a	n/a	n/a	23,500	n/a	n/a	n/a	n/a
Czech Republic	12,000	4000	n/a	13,100	3,380	n/a	n/a	3310	2900
Denmark	n/a	n/a	n/a	~120	n/a	~70	n/a	n/a	26
Estonia	n/a	n/a	n/a	1500	375	n/a	1253	163	143
Finland	48,000	25,000	20,000	22,645	16,915	16,024	22,646	16,916	16,024
France	270,000	100,000	70,000	~200,000	n/a	~98,000	200,000	120,000	91,600
Germany	120,000	25,000	20,000	120,000	24,700	~20,000	120,000	36,000	11,040
Greece	80,000	15,000	12,000	80,000	20,000	15,000	n/a	n/a	17,000
Hungary	5000	n/a	n/a	7446	4590	n/a	7446	4590	4068
Ireland	1000	1000	n/a	1400	1180	950	n/a	847	847
Italy	340,000	105,000	65,000	190,000	60,000	50,000	200,000	160,000	80,000
Latvia	6000	5000	n/a	7200	4000	3900	6940	5360	3900
Lithuania	2000	1000	n/a	6034	2464	1295	6034	2090	1287
Luxembourg	n/a	n/a	n/a	175	140	137	175	140	137
Malta	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Netherlands	n/a	n/a	n/a	11,396	< 110 MW	~130	3900	250	1000
Poland	23,000	14,000	7000	25,000	12,000	7000	25,000	13,750	8500
Portugal	32,000	25,000	20,000	32,150	24,500	19,800	n/a	29,070	21,784
Romania	70,000	40,000	30,000	70,000	40,000	n/a	70,000	34,509	20,704
Slovakia	10,000	7000	n/a	10,000	> 6607	~6000	n/a	7560	6600
Slovenia	13,000	6000	n/a	12,500	8800	6125	12,500	8800	6125
Spain	138,000	70,000	41,000	162,000	61,000	37,000	162,000	68,500	44,000
Sweden	176,000	130,000	90,000	200,000	130,000	90,000	200,000	130,000	94,000
United Kingdom	40,000	1000	n/a	n/a	~4000 MW	n/a	31,378	27,203	18,990

[a] ESHA – European Small Hydropower Association, aggregated value of indicated small (less or equal to 10 MW) and large (greater than 10 MW) plants.
[b] GTC – Gross theoretical capability [GWh/year], TEP – technically exploitable potential [GWh/year], EFP – economically feasible potential [GWh/year].

(originally 3″, resampled to 100 m) digital elevation data of Earth, obtained by the Shuttle Radar Topography Mission (SRTM) [30–32].

Three data sources of continental **drainage networks** were applied in different resolutions during the complex modelling. A derived product of SRTM data, the Pan-European River and Catchment Database [14] was applied in the hydropower-site selection analysis. In the frame of the Catchment Characterization and Modelling (CCM) activity, a 100 m gridded flow network was extracted from the digital elevation model (DEM) using algorithms based on the concepts of mathematical morphology [33,34]. The 1 km gridded flow network, applied in the hydrological modelling, has been developed in the frame of a project setting up the European Catchment-based Information System (CIS) [13].

The 5 km gridded data on representative **drain directions** was derived for continental hydrologic modelling, and based on the processed and harmonized components of formerly mentioned SRTM, CCM and CIS data sets [15]. Both drainage networks (in 1 km and 5 km resolutions) formed essential components of the LISFLOOD Hydrological Model [16], which provided simulated river discharge data [17] for assessing hydropower potential.

Auxiliary data sets on **land cover** [35] and the publically available **Global Reservoir and Dam Database** [36,37] and high resolution satellite imagery (OpenLayers, Google Maps) were involved into the final selection of suitable locations.

3. Methodology of setting up a spatial decision supporting system and geo-database for modelling

In order for overlapping and analyzing the different spatial data layers from different sources (Fig. 1, input data), the model was set up using a common reference system (European Terrestrial Reference System 89, Lambert Azimuthal Equal Area), which is corresponding to the European standards [38]. The spatial resolution of the DEM and the CCM river network data was kept in the source 100 m [14]. A downscaling method has been developed to obtain discharge information in the same resolution based on the coarser resolution hydrological model data. The method is described later in this section. The geographic extent of the model covers the member states of the European Union; however, the applied hydrological model [17] did not give estimates for Cyprus and the final version of the Renewable Energy Action Plan of Croatia was also not available at the moment of writing this paper for validation purposes.

3.1. Elevation and river network

The cell-based flow model, representing the river network in 100 m resolution, was derived from the processed elevation model (SRTM) and the flow directions defined by the CCM project (Fig. 1, geo-processing developed previously). The contributing area of each river cell (Fig. 3a) and the stream gradient from each upstream river cell to the next downstream cell has also been calculated (Fig. 3b), according to the flow directions (orthogonal or diagonal cells, difference in elevation). This elevation drop along the stream is a crucial quantity entering in the calculation of maximum potential hydropower, as the physically measurable, potential gross head.

Due to the coarser spatial resolution (5 km) of the hydrological model and the geographical differences between the generalized, representative 5 km flow model and the 100 m river network, two auxiliary elevation data layers have been generated and applied in the first estimation of potential hydropower production.

The reduced-resolution elevation layers represented the maximum values of elevation drop that occurred along the 100 m stream network encompassed by the 5 km × 5 km pixel belonging to the hydrological model. A data set showing the local maximum

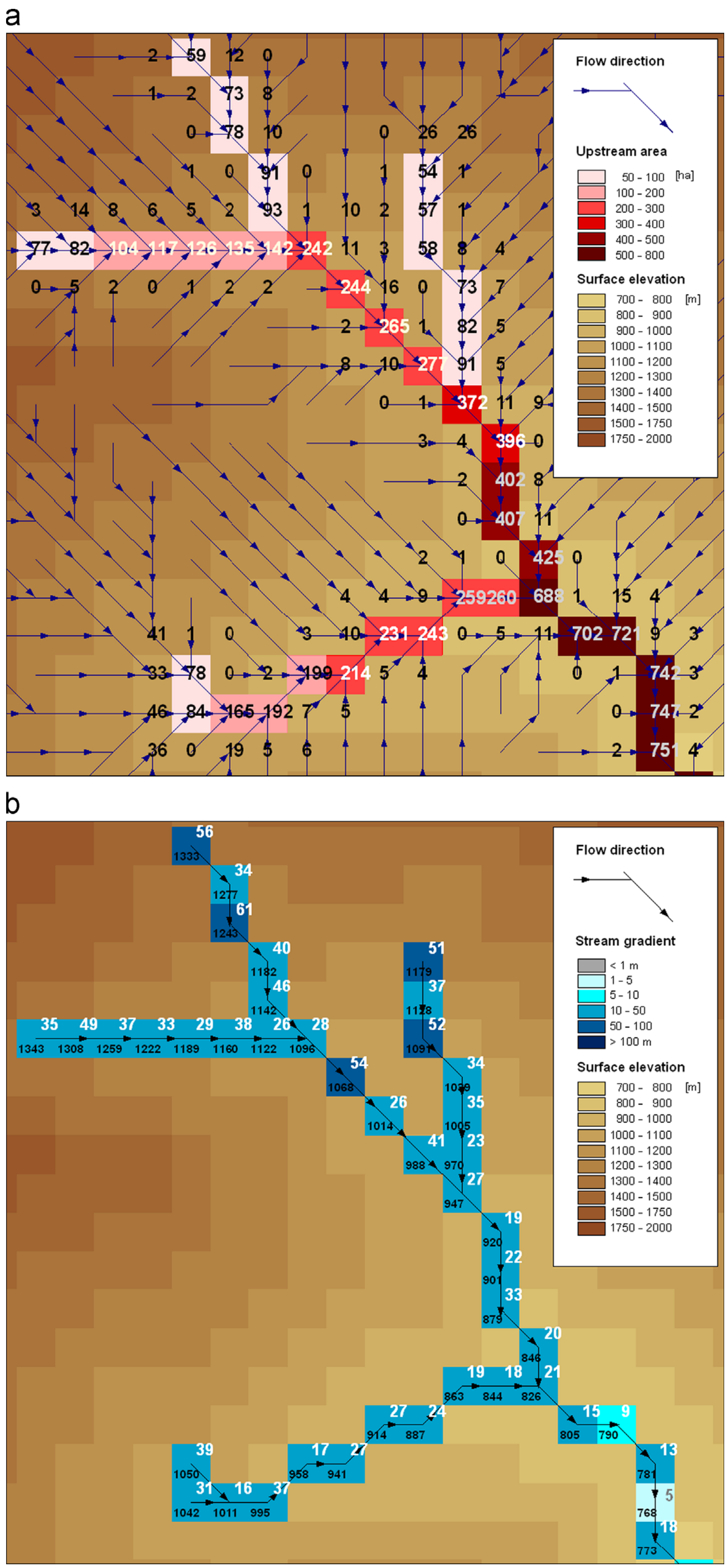

Fig. 3. (a) Flow direction and derived contributing area of river cells. The numbers indicate the catchment area in hectare (number of upstream pixels in the model). Resolution: 100 m. (b) Elevation drop along the stream. The black numbers show the elevation above sea level, the white numbers show the relative difference in elevation comparing to the next cell downstream.

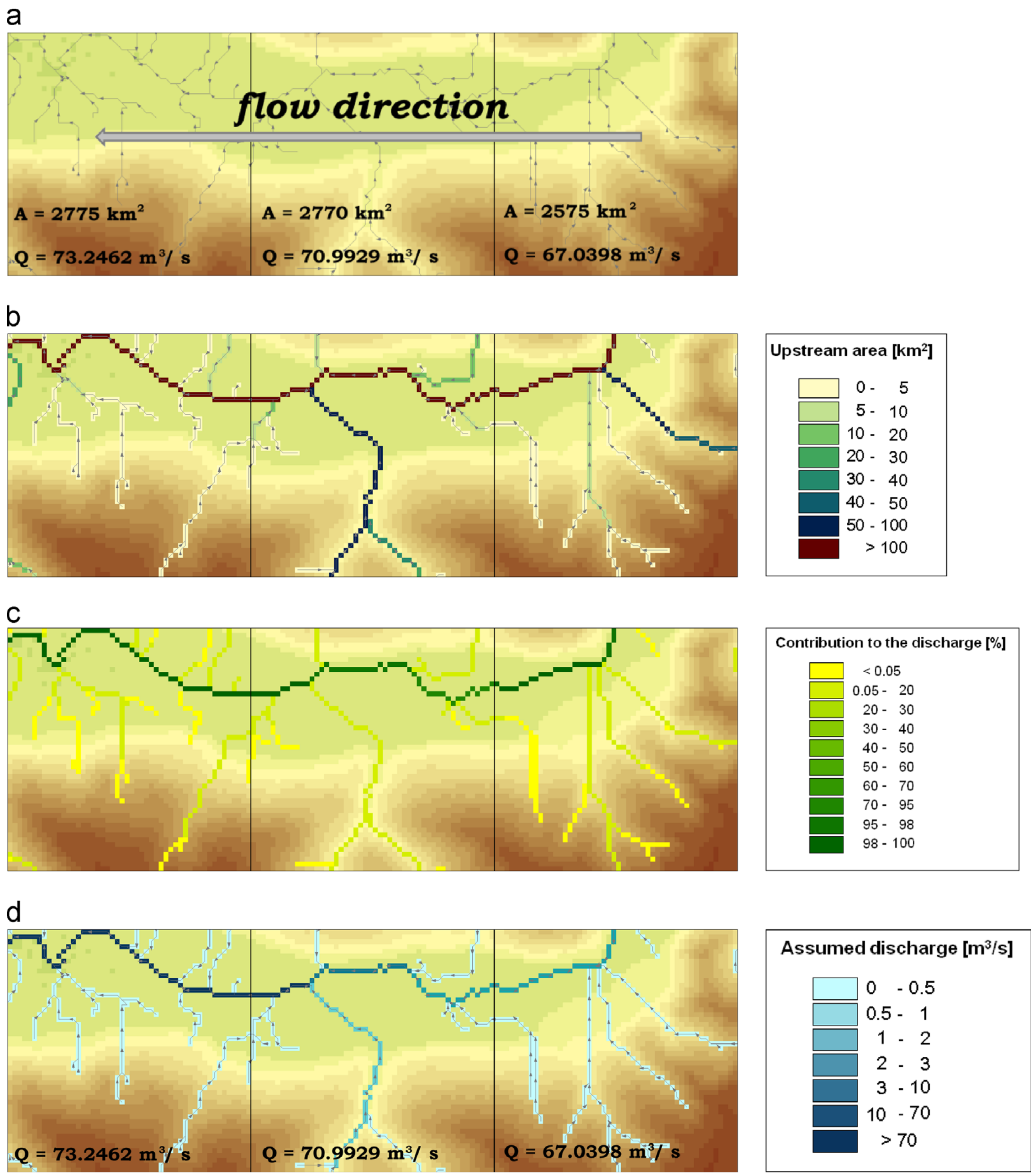

Fig. 4. (a) Three cells of the hydrological model with the contributing (upstream) area (A) and the estimated discharge values (Q) in 5 km resolution. (Derived and validated river network (narrow grey lines) based on CCM data. In the background: the processed digital elevation model in 100 m resolution (SRTM) which formed the basis for catchment delineation.) (b) Defined drainage area above each river cell based on the flow direction model in 100 m resolution. (c) Assuming linearity between adjacent river cells belonging to the same river system, proportional area of the total upstream area may predict the proportional contribution to the discharge. (d) Assuming continuity in the flow and according to the law of conservation of mass, an estimate of discharge characterizing the modelled rivers can be calculated.

drop was applied in the estimation of maximum potential hydropower as 'gross head'. A smoother, aggregated elevation data set, which first averaged the elevation drops in 100 m for 1 km, and then presented the 1 km maximum values in 5 km, has been applied for masking the relatively flat areas out.

The threshold for this latter smoothing procedure has been set in 5 m and within 1000 m (0.5% surface gradient) (Fig. 1) with the aim of mitigating the misleading influence of the surface model, which contains the elevation data of land objects (i.e. buildings, forest canopy) too. It is worth reminding that such an approach leads naturally to the analysis of hydro installations needing a significant water drop, but this does not imply that the "discarded" river tracts are totally unsuitable for energy purposes. Low-gradient rivers with higher discharge might be suitable for installation of lowland reservoir-supported, low-head hydroelectric stations, where generating method is, nevertheless, not addressed by the current study.

3.2. Modelled discharge

The processed data on river discharge (Fig. 1, input data) have been resulted by the hydrological simulations used the LISFLOOD model [16] forced by the ECHAM5-r3 Global Circulation Model (GCM), KNMI-RACMO2 Regional Climate Model (RCM) following the A1B IPCC climate scenario [17]. 50,769 Data files representing the modelled daily average discharge (m^3/s) of 140 years, between 1st of January 1961 and 31st of December 2099 [17], have been processed for the spatial resolution of 5 km. Two main data subsets were prepared (2003–2012, 2013–2022) in order to map

and classify the potential hydropower sites. The selected time periods covered the time range of available control data set (2005–2020) as reported in the National Renewable Energy Action Plans (NREAPs) [3,4]. Based on the modelled daily average data, the monthly mean discharge values had been calculated for both time periods. Areas, where the monthly mean discharge did not exceed the $2\ m^3/s$ in the representative $5\ km \times 5\ km$ cell for at least 6 months per year, were excluded (Fig. 1). The obtained monthly mean values, as the parameter of flow rate, have also been applied in the calculation of 'technical potential hydropower', and their seasonal distribution was used to give an estimate of the annual duration and applicability of the location in months.

3.3. Data downscaling

Due to the different physical and descriptive characteristics, the coarser resolution hydrological flow network modelling the mass of running water potentially available within a $5\ km \times 5\ km$ cell, and the applied river network (CCM) were not overlapping. In order to estimate discharge values also for each section of the river network in a finer resolution, a downscaling method was developed. The idea was based on the assumption that short river segments (i.e. adjacent cells of modelled main rivers and tributaries) within the same river system can be characterized by similar hydrographical behaviour, and they are contributing to the discharge of down-stream sections proportionally to the size of their contributing area. The following equation summarizes the applied concept:

$$\text{Discharge}_{100\text{ m rivercell}} = \frac{\text{Discharge}_{5\text{ km rivercell}}}{\text{Upstream area}_{5\text{ km rivercell}}} \times \text{Upstream area}_{100\text{ m rivercell}}$$

The task was completed in four main steps as presented in Fig. 4.

This procedure resulted in the assumed discharge data base, associated to each cell of the 100 m river network and was repeated for each monthly average in the two time periods in order to develop a monthly average picture of the rivers flow in the European territory.

3.4. Calculation of technical potential hydropower

This study considers hydropower plants sizing between 100 kilowatts (kW) and 10 megawatts (MW). A run-of-river hydro plant does not store water and it makes use of hydro turbines that can operate on wide flow ranges. In the model we assumed the use of a Kaplan turbine in case of low or medium hydraulic heads (2–20 m) and medium flows (3–10 m^3/s) [39–43]. With relatively high hydraulic head (greater than 25 m) and low flow (less than 1 m^3/s) a Pelton turbine could be applied [39–43]; however this range of flow is not considered in our model due to the uncertainty arising from the applied hydrological source [17] summing up with additional uncertainties introduced by the data downscaling process described in the previous section. The developed model considers "one turbine for one suitable location".

The 'maximum potential hydropower' could be idealistically generated using the total stream flow; however in this exercise the more policy relevant 'technical potential hydropower' is estimated, taking only that volume (min. 2 and 10 m^3/s) out from the natural river course that is technically necessary for the continuous operation of the water turbines capable of providing the targeted power [39,40]. Such technical potential could be generated using the average flow rate needed by the suggested turbines [39–43] from the total stream flow and the maximum gradient along the whole river based on the following equation:

$$P = m \times g \times H_{net} \times \text{System efficiency}$$

where

P: power, measured in Watts ($W = kg\ m^2\ s^{-3}$).
m: mass flow rate in $kg\ s^{-1}$ (numerically identical to the flow rate in litres).
g: gravitational acceleration, set at $9.81\ m\ s^{-2}$.
H_{net}: net head (m). This is the gross head (H_{gross}) physically measured at the site minus any head losses.

System efficiency: the product of all of the component efficiencies, which are normally the turbine, drive system and generator. In order to determine a realistic power output, the theoretical power must be multiplied by an efficiency factor of 0.5–0.7, depending on the capacity and type of system [39–43].

The optimum penstock pipe size tends to be a site-specific decision, and several aspects should be evaluated (i.e. diameter, friction loss). The optimum diameter can be identified by analyzing the mean and peak flow rates [43].

Based on the examples of practical guides [39–43] head losses can be assumed to be about 10%, so $H_{net} = H_{gross} \times 0.90$. For a 'typical' small hydro system the turbine efficiency would be 80%, drive efficiency 95% and generator efficiency 90%, so the overall system efficiency would be $0.80 \times 0.95 \times 0.90 = 0.684$ or 68.4%.

In summary, a location was considered potentially interesting for setting a mini or small hydro plant if the location was modelled as capable of producing at least 100 kW.

Where the potential production is up to 1 MW the site is considered suitable for a mini hydro station, where it exceeds 1 MW, the site is considered suitable for a small hydro station. Hydro-geographically the selected locations are the subset of the river segments, where

– the surface gradient of the surrounding area is at least 0.5 % (excluding flat areas);
– the average flow rate is at least $2\ m^3/s$ for at least 6 months; and
– the gross head is at least 12 m or, as an alternative, the flow rate is at least 10 m^3/s and the gross head is at least 6 m (see Fig. 1 for details).

Moreover, two additional constraints were applied considering the spatial resolution of the input data. Regarding the physical limitations of the digital surface model (100 m horizontal and 1 m vertical resolution), river sections where the drop between adjacent river cells was smaller than 6 m (app. 5 m estimated gross hydraulic head) were not considered as a suitable location (Fig. 1). Similarly, the $5\ km \times 5\ km$ resolution hydrological model determined the smallest drainage basin (25 km^2) having the capability of producing the minimum, technically needed flow rate in most of the European countries. River sections of the drier Iberian Peninsula, the Mediterranean and Balkan region required larger contributing area (the mean was 100 km^2) for fulfilling the 'at least 2 m^3/s discharge for at least 6 months' criteria. Smaller basins less than 25 km^2 and 100 km^2, respectively, were then excluded from further analysis in order to guarantee that no actually dry valleys are selected, not even if the linear downscaling step, described in Section 3.3, would estimate enough discharge for energy production.

Defining suitable locations of mini and small hydropower stations, the river sections represented by the CCM network were analyzed and sites showing the optimal performance within 1 km neighbourhood were selected. Such a predefined minimal distance was inspired by the density of similar sized hydroelectric stations along the tributaries of Upper-Danube (e.g., Iller, Lech) where the natural potentials are extensively exploited [26,44,45].

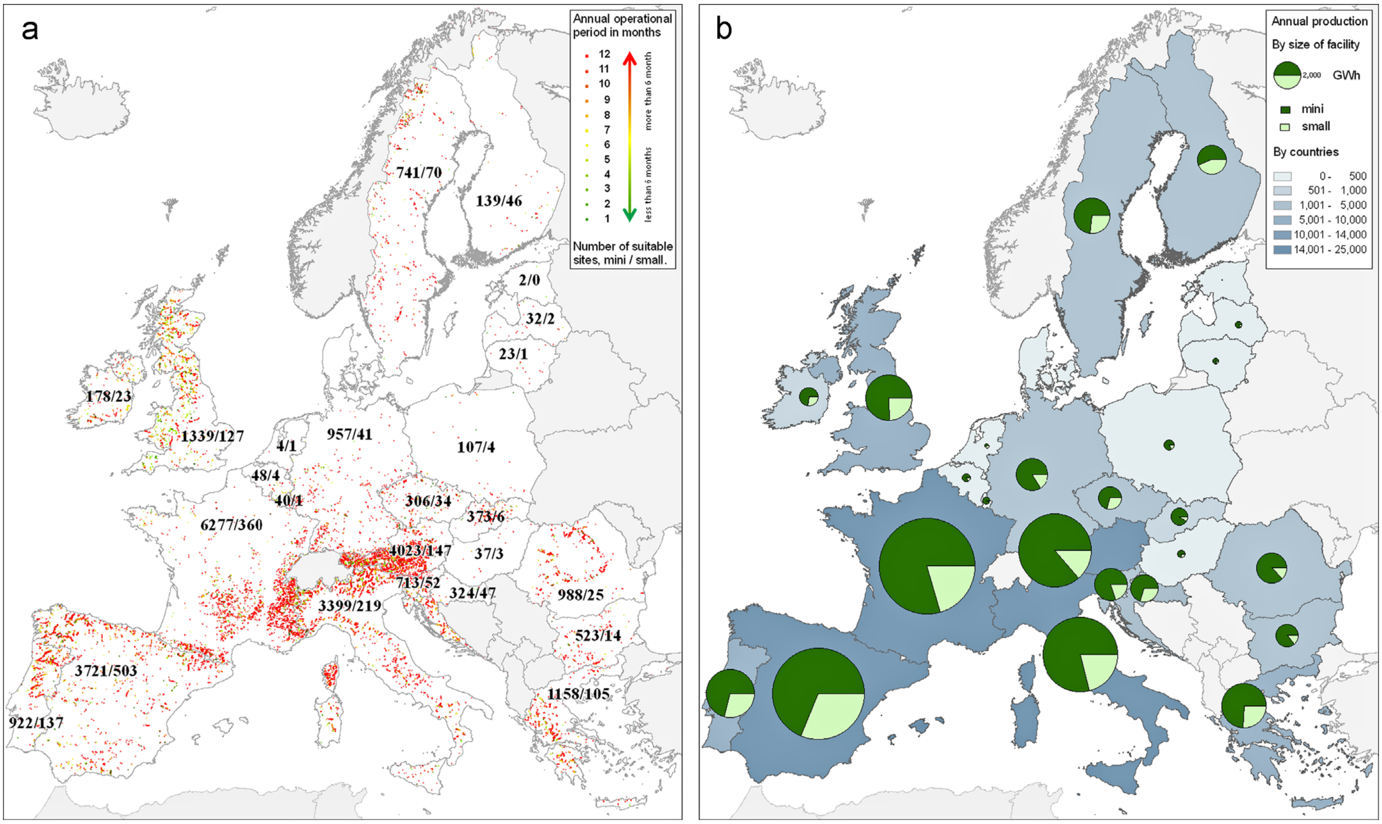

Fig. 5. Suitability map of mini and small hydroelectric stations with installed capacity between 100 kW and 10 MW, locations and annual operational period based on the modelled maximum potential hydropower (A). The colours indicate the annual availability of the location in months. Map resolution is 1 km. Area in grey is out of model. The map on the right shows the country-based potential production based on the presented hydrographical-technical approach.

Table 2
Number of modelled suitable locations according to the classification based on operational time and production capacity. The rightmost column shows the number of existing mini and small hydropower stations (run-of-river, dam/reservoir-type, pumped).

Country	MHPP_T1[a]	SHPP_T1	MHPP_T2	SHPP_T2	MSHPP[b] P < 10 MW
Austria	4023	146	4023	147	2666
Belgium	49	4	47	3	83
Bulgaria	522	14	523	14	120
Czech Republic	310	34	301	34	1413
Germany	953	40	960	41	6548
Denmark					34
Estonia	2		2		41
Spain	3728	505	3713	500	1152
Finland	137	45	141	47	152
France	6246	348	6308	372	1423
Greece	1148	96	1168	113	83
Croatia	325	46	322	48	32
Hungary	37	3	37	3	40
Irish Republic	179	22	177	23	59
Italy	3395	212	3403	226	1853
Lithuania	23	1	23	1	72
Luxembourg	40	1	39		24
Latvia	32	2	32	2	146
Netherlands	4	1	4	1	10
Poland	110	4	104	4	643
Portugal	934	141	909	133	78
Romania	994	26	981	24	240
Sweden	731	69	751	70	1462
Slovenia	713	52	713	52	511
Slovakia	377	8	368	4	267
United Kingdom	1360	130	1318	124	142

[a] Modelled estimated number, MHPP_T1 – mini hydro (100 kW–1 MW) for the first modelled time slice, SHPP_T1 – small hydro (1–10 MW) for the first modelled time slice, MHPP_T2 – mini hydro for the second modelled time slice, SHPP_T2 – small hydro for the second modelled time slice.
[b] *Source*: ESHA – European Small Hydropower Association, MSHPP – mini and small hydropower plants.

4. Results: suitability mapping and hydro plants allocation

Following the criteria described in Section 3 suitability maps for both mini and small hydro were developed with the spatial resolution of 1 km on the whole European area of the study. Fig. 5 shows the potential locations of mini and small hydropower plants (A) and their potential electricity production by countries (B) based on the input parameters of monthly mean discharge data based on modelled daily average discharge [17], the determined elevation drop along the stream based on the processed elevation and CCM data [14]. The overall system efficiency of the model has been set to 65%.

Based on the estimated annual operation period and the capacity, suitable locations were further classified in four classes: (1) mini hydro (100 kW–1 MW) for at least 6 months, (2) mini hydro for less than 6 months, (3) small hydro (1–10 MW) for at least 6 months, and (4) small hydro for less than 6 months. For each country, number of location has been calculated based on the modelled discharge data of the time periods 2003–2012 and 2013–2022. Table 2 shows the number of suitable sites in mini and small categories together with data on actual plants obtained by ESHA.

4.1. Site numbers

The model gives meaningful projection on the potential sites of mini and small hydro locations (MSH locations) in Europe that can contribute to the policy discussion over the future role of hydro-energy. By following the description of the paper its transparent procedure can be scrutinized by all stakeholders.

The countries where ESHA accounts for more than 100 existing MSH locations the model projects high number of potential new sites: on average from 140% to 10-fold (Austria 1.5; France 4.4; Slovakia and Slovenia 1.4; UK 9.6; for the Mediterranean and Balkan countries: Italy 1.8; Spain 3.2; Romania 4.1; Bulgaria 4.4). For Greece the number is 13.8 but it is probably due to the low base number: the ESHA figure for this country is only 83. Real outlier countries are Germany, Poland (15%) and Sweden (50%). For these countries the model predicts a lower figure than the ESHA number. Analyzing the German ESHA figure points out that in Germany there are quite a high share of reservoir type of hydro-power plants [44,45] that the presented model cannot project. Moreover in Germany there are quite many rivers where dams have been built on close sections of the rivers [36,37], and the reservoirs are used for a number of hydro management purposes

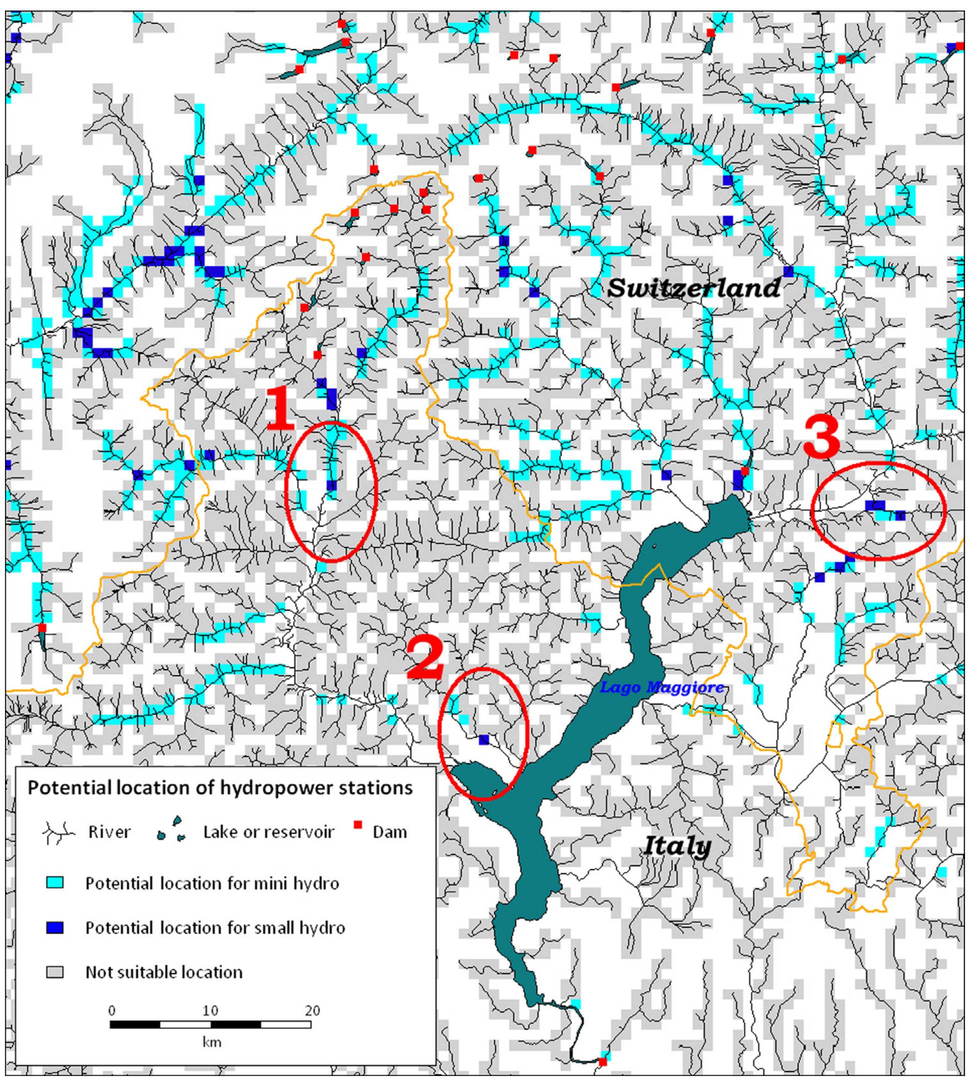

Fig. 6. Modelled potential locations of mini (100 kW–1 MW) and small (1–10 MW) hydropower stations. Spatial pattern of selected suitable locations near Lago Maggiore (Italy/Switzerland).
Source of Reservoir/Dam layers: GRanDv1, [36].

Fig. 7. Locations marked in Fig. 6: (1) River Toce close to Pontemaglio (Italy) (Google Street View), (2) Torrente San Bernardino (Italy) (Photo: Dara, J.), (3) River Morobbia (Switzerland) (Photo: Bistoletti, G.).

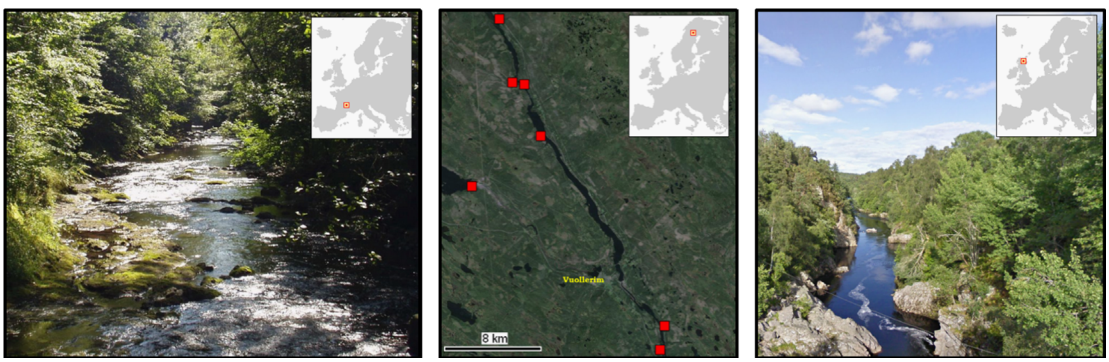

Fig. 8. Suitable locations in France, Sweden and in the UK. The geographic coordinates (longitude, latitude) are given in brackets. (1) La Jordanne, close to Lascelle in the region of Auvergne, France (45.037, 2.593); (2) Lule River (Luleälven), close to Vuollerim, Sweden (66.4, 20.7); (3) River Findhorn, Old Military Road, close to Dulsie, Scotland, United Kingdom (57.452, −3.777).
Sources: (1) Google Maps, credit: lasdou, (2) Google Maps, and (3) Google Street View.

Fig. 9. Higher land object (forest along the river) that could influence the definition of “hydraulic head” derived from the surface model.

(e.g., recreational and energy). The explanation in Sweden also relies on the relatively large number of reservoir type hydropower sites [36,37]. It also shows that if proper regulatory environment is in place, the number of MSH plants can even be further increased. The low Polish projection number shows that in case of mostly flat countries the applied technique can result in low projections due to the coarseness of the hydrology/elevation inputs.

4.2. Locations in examples

Fig. 6 shows the spatial pattern of selected locations in the mixed Alpine-lowland Swiss-Italian cross-border region near Lago Maggiore. The related subset of dams and reservoirs from the Global Reservoir and Dam Database [36] is also visualized indicating that the developed site selection method found mostly new locations for run-of-river type stations. Fig. 7 shows the river courses and locations marked by 1, 2, 3 in Fig. 6

Fig. 8 shows three further examples of suitable sites, selected randomly in France, Sweden and in the UK.

Locations could be mistakenly concerned as suitable due to the characteristics of the surface model (i.e., land objects are also visualized, 100 m resolution). Fig. 9 shows a location where the canopy of the riparian forest would mislead the selection algorithm, but most of the misleading situations like this were eliminated by excluding flat areas (Fig. 1) and applying auxiliary data sets on land cover. More detailed data on geometry of river beds and elevation models free of land objects would assist a more precise site selection.

Table 3
Annual production (GWh) of mini and small (MS) stations based on NREAPs (MSYEAR), modelled values for two time periods (in italic), and the gross theoretical (GTP), technically exploitable (TEP) and economically feasible (EFP) potential based on the ESHA database[a].

COUNTRY	MS2005	MS2010	MS2015	MS2020	2002–2012	2013–2022	ESHA_GTP	ESHA_TEP	ESHA_EFP
Austria	4695	5529	5655	6041	*14,579*	*14,662*	15,000	11,000	9500
Belgium	208	216	233	263	*178*	*156*	n/a	n/a	293
Bulgaria	475	630	713	769	*1398*	*1391*	1527	n/a	1070
Cyprus	n/a	n/a	n/a	n/a	*0*	*0*	n/a	n/a	n/a
Czech Republic	564	900	1147	1309	*1466*	*1400*	n/a	1500	1300
Germany	6717	6350	6700	7050	*2830*	*2745*	39,800	11,950	9190
Denmark	23	31	31	31	*0*	*0*	n/a	n/a	26
Estonia	20	26	30	30	*2*	*2*	1170	80	60
Spain	7152	4669	5547	6527	*22,945*	*22,873*	n/a	7500	7000
Finland	1400	1440	1440	1460	*2214*	*2289*	2265	1692	1602
France	7907	7460	7605	7749	*24,838*	*25,335*	20,000	12,000	10,000
Greece	324	705	844	983	*5149*	*5577*	n/a	n/a	2000
Croatia	n/a	n/a	n/a	n/a	*2068*	*2028*	n/a	n/a	n/a
Hungary	n/a	36	38	79	*145*	*138*	420	279	68
Irish Republic	n/a	n/a	n/a	n/a	*910*	*896*	n/a	237	237
Italy	9242	9196	10,636	12,077	*15,025*	*15,477*	66,000	52,800	26,400
Lithuania	66	79	93	117	*89*	*86*	2094	854	287
Luxembourg	98	106	106	124	*147*	*122*	175	140	137
Latvia	62	62	66	70	*117*	*115*	1160	730	280
Malta	n/a	n/a	n/a	n/a	*0*	*0*	n/a	n/a	n/a
Netherlands	5	5	62	62	*57*	*57*	n/a	250	140
Poland	862	891	1051	1211	*307*	*291*	13,400	5100	2500
Portugal	381	827	1108	1511	*6417*	*6180*	7088	5670	3024
Romania	599	719	1189	1359	*2622*	*2414*	8273	4080	2447
Sweden	3265	3265	3265	3265	*3456*	*3526*	15,000	11,000	9000
Slovenia	606	454	517	540	*2934*	*2868*	2000	1100	475
Slovakia	278	239	363	543	*833*	*725*	n/a	1220	1000
United Kingdom	n/a	1970	2060	3230	*6027*	*5727*	8988	7736	4903

[a] The NREAPs and ESHA database provide statistics based on installed capacity only and do not distinguish between generation types (i.e., run-of-river, dam/reservoir, pumped).

5. Results: hydrographical-technical potential

In order to estimate the potential annual production (GWh) of the selected suitable sites, the calculated local technical capacity was multiplied by the modelled possible operational period per year. The results were summed up to country level and compared with the reported figures in the National Renewable Energy Action Plans (NREAPs) [3,4] and in the ESHA database [25]. Table 3 shows the annual production (GWh) of small and mini hydropower plants as planned and reported by the Member States of the European Union between 2005 and 2020, the modelled values resulted by the analyses described in this paper, and the gross theoretical, technically exploitable and economically feasible potentials of mini and small hydropower stations extracted from the ESHA database. It is worth mentioning that neither details of calculations nor methodological descriptions are in general available for both the national estimates and statistical figures.

5.1. Production

The performed analyses provided production figures that are closely positioned between the gross theoretical potential and technical potential figures given by the ESHA, and they roughly surpass three times the actual figures reported by the Member States. This shows the massive additional capability of the small and mini hydropower in the renewable energy portfolio to complement the dynamic PV and wind capacities. The country specific data shows substantial additional production in the dominant hydro energy producer countries: in case of Austria, Spain, France and the UK the figures are three times, for Italy it is twice as much as the actual figures. The German and Polish figures are smaller due to the reasons described in the section on the site numbers.

The potential production figures estimated here confirm some of technical potential figures provided by ESHA (Table 3, right columns) e.g., for Portugal, Austria and UK. Somewhat higher technical potentials are found for France and Slovenia, but for some important hydro-electricity producing countries (like for Italy and Sweden) estimates show much lower potential than the ESHA figures (Table 3). A detailed analysis of these differences has not been possible due to the scarce details (e.g., about generation type) provided on the methodological basis of ESHA figures. Nevertheless, it is worth noticing that the results provided here are not limited to overall theoretical country figures, but also include assessments of the geographical locations of the proposed suitable sites. Such a result is of overwhelming importance to support the policy dialogue at every level.

6. Conclusions and outlook

The present study describes and validates a replicable procedure that approaches the European hydro energy potential estimate with a novel GIS-based analysis, using databases that were independently developed with other purposes in mind. The main added value coming from this approach is the assessment of not only a hydrographical-technical potential, but the actual suitable sites of the proposed hydro stations, a data layer easy to be scrutinized and interpreted by most of the stakeholders.

The best way to utilize the result of the study in this process would be to compare the proposed locations to the other technical potential estimates. However most often the related literature [20–22,29] does not go beyond the overall technical potentials (given in GW or GWh) for each country generally lacking of the detailed site locations and not distinguishing between different generation types (i.e., run-of-river, dam/reservoir, pumped). As site specific data were available only for the operating small and mini

hydropower plants, the scope of the comparison and the model calibration is determined by these existing datasets [22,26,44,45] resulting in special focus on the run-of-river concept for both mini and small hydro plants.

Overall the model shows that such a technology can in principle provide a huge additional capacity to be added to the comprehensive electricity generation portfolio in the EU countries where significant increase of intermittent RE is foreseen. Our analysis shows that while the new proposed small and mini hydro sites cannot level out the foreseen wind production in regions which can be characterized with dominantly flat areas (Denmark, Holland, Belgium), but it can be a significant portfolio complement in the UK, Ireland and North of Portugal. On the other hand, the dynamically growing photovoltaic solar development in Italy, Spain and Greece can be suitably complemented with considerable number of small and mini hydro generation. These local production mix can considerablly reduce the necessary upgrade of the transmission system due to the RE integration requirements. In certain countries this compatibility can be analyzed only on a more local level: in Germany there are regions characterized with high wind and PV capacities, but as the potential hydro site are distributed unevenly, their compatibility could be assessed only if the PV and wind site information are available. Having access to more detailed geographical data on existing and planned wind and PV sites/capacities (with a similar resolution to the present analysis) the methodology would be capable of giving hands on information on the most suitable sites that could form the best compatible power mix in the given regions.

Table 2 also shows that the same procedure identified quite a huge potential in extending especially the mini hydro generation in Europe. The analysis points out that almost all the New Member States and the Mediterranean countries make use of only the minor part of their mini hydro potential.

In the Eastern European countries this can be explained by the historical dominance of the large hydropower plants over the smaller production sites in the central planning. Large capacity sites had been prioritized in these former socialist countries. This can also be tracked down in the relative difference in the number of these mini sites in new and the old Federal States of Germany [44,45] as well. Since the unification of Germany the number of mini power plants has started to grow in these new Federal States (former East Germany). As in the rest of Germany (former West Germany) this number decreased; the two territories draw nearer to one another [44,45].

6.1. Towards environmental feasibility

A detailed assessment of the additional possible constraints to hydro potential exploitation was not in the scope of the present study, mostly because of the amount of additional data on such an issue would have required to be discussed at pan-European scale.

Nevertheless, some broad analysis in this direction was also performed. For instance, exploring further the data, the identified locations were superposed with land cover categories (Corine Land Cover 2006). Near three-quarter of all the sites fall into the different forest categories, and an additional 18% into the heterogeneous agricultural areas that can be classified into less intensive production categories, and only a negligible part is close to urban fabric.

A consequent exploration of the data in order to further streamline the potential sites could consist in the identification of the overlap of the proposed sites with the different nature protection areas. Our initial analysis shows that less than 30% of both the small and the mini hydro sites fall on the territory of nature-protected areas of various protection levels (Natura2000 network). Although the segment that can already be excluded from the recommended potential location is not negligible, already this level of data exploration shows that nature protection purposes are not the major prohibiting factor in the further expansion of the small and mini hydro sites. The overlay with the various water protection zones (the classification that is foreseen in the WFD) would probably impact the number of potential sites.

However, further examination and exclusion of areas of other thematic data layers (recreation, amenity) could also provide further information on the sites. Overlaying the proposed sites with already existing solar and wind farms, and with network data (i.e., congestion data) could also help to propose a more acceptable ranking procedure among the sites.

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Annex I. Differences between small and large hydroelectric installations

Hydropower projects can be classified by generating capacity and applied generating methods. The definition of a small hydro

Table I
Differences between small and large hydroelectric installations.

	Small Hydro (run-of-river)	Large Hydro (reservoir type)
Electricity generating methods [A2]	According to the available hydrological fluctuations of the site, having limited storage capacity	Involving damming water and creating reservoirs with significant storage capacity
Grid-connected or stand-alone systems [A1,A2]	Can be off-grid, stand-alone system or connected to isolated minigrids (local consumers)	Usually connected to major electricity grid (remote consumers)
Usual generating capacity [A1,A2]	< 10 MW (small hydro) 100 kW–1 MW (mini hydro)	> 10 MW (> 100 MW)
Output [A3]	Generally constant over short time periods (minutes to hours) but varies over longer periods (days to seasons), predictable based on hydro-meteorological forecast	Dispatchable having ability to specify generator output
Preparatory phase/implementation [A4,A5]	Can be initiated and projected by private person or private company, legal personality or community level	Usually involves complex planning on national or international level
Social aspects, impacts and risks, public acceptance [A2,A6–A9]	Can serve a smaller, local community, or a remote industrial activity providing better electricity access to remote or isolated areas small hydro facilities, especially using existing	The most ubiquitous large renewable energy source (RES), multi-purpose use e.g. flood retention, irrigation, recreational purposes severely criticized by the public,

Table I (*continued*)

	Small Hydro (run-of-river)	Large Hydro (reservoir type)
	civil structures (e.g. old mill workings) are generally acceptable systems integrated into the landscape and river-rehabilitation and renewable energy enjoy high public acceptance	forced population displacement and impoverishment, boomtown formation around major constructions, downstream unanticipated changes in agro-production systems, loss of cultural heritage assets
Environmental integration [A1,A2,A10,A11]	Relatively little change in the stream channel and flow an eventual small storage has very low impact on oxygen depletion, temperature increase, flow decrease and upstream migration little impact on the landscape	Large hydropower can have large impacts on upstream and downstream habitats, depending on water flows affected by dams, evaporation losses notable change in the landscape (high dam, large water body)
Accumulated environmental impacts [A12–A14]	Overlapping criteria of sustainability covering environmental, economical and also socio-political aspects	Large hydropower could have a lower degree of impacts than many small-scale projects
Land use footprint (area per unit of electricity generated) [A15,A16]	Can be very low (0.1 ha/MW)	Can be very high (800 ha/MW)
GHG emission (because of construction e.g., blasting, excavation, displacement of material, cement manufacturing, transport etc.) [A17]	1–3 kt eq. CO_2/TWh	10–15 kt eq. CO_2/TWh
Life-cycle emissions of GHGs for electricity generation [A2]	1–18 g CO_2-eq/kWh	2–48 g CO_2-eq/kWh

Table II
Investment costs for the Hydro Power plants (US$ 2008).
Source: International Energy Agency ETSAP – Technology Brief E12 – May 2010 – http://www.etsap.org.

Hydro Power plant category	Minimum ($/kWe)	Maximum ($/kWe)	Typical ($/kWe)
Large (> 10 MWe)	1750	6250	4000
Small (1–10 MWe)	2000	7500	4500
Very small (≤ 1 MWe)	2500	10,000	5000

Table III
Operation and maintenance costs of hydropower are between 1.5% and 2.5% of investment cost per year.
Source: International Energy Agency ETSAP – Technology Brief E12 – May 2010 – http://www.etsap.org.

Hydro Power plant category	Minimum ($/MWh)	Maximum ($/MWh)	Typical ($/MWh)
Large (> 10 MWe)	40	110	75
Small (1–10 MWe)	45	120	83
Very small (≤ 1 MWe)	55	185	90

project varies, but the usual generating capacity does not exceed 10 MW driven by run-of river systems. Mini hydro systems, with capacity between 100 kW and 1 MW, can form a subdivision. Large-scale hydropower plants, that usually involve dams, can provide more than 100 MW and typically feeding into a major electricity grid providing electricity [A1,A2]. An overview of characteristic differences between small and large hydroelectric installations is given in Table I considering several technical, social, environmental aspects. Typical investment and operational costs are given in Tables II and III.

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